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Assessing the sustainability of the UK society using thermodynamic concepts: Part 1

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ABSTRACT

This paper provides a concise overview of the influence of human activity within the UK society on resource consumption and the subsequent effects on the environment. The concept of the Multi Scale Integrated Analysis of Societal Metabolism (MSIASM) is applied in order to elucidate the evolution of the UK economy for the period between 1981 and 2004. Our findings highlight the transition to a service-based economy and the disproportionate increase of energy demand when compared to the overall population increase. Emergy synthesis is applied in order to understand the production and consumption patterns and the environmental support required to sustain human activity within the UK for the year 2004. Generally speaking the UK society greatly benefits from its significant natural resources with 44.3% of the total emergy used coming from home sources and 29.1% from locally renewable sources. Interestingly enough, despite its significant natural resources, the UK economy, seems to be a net emergy importer by 638.5×10^{21} seJ. Furthermore, the current economic activity is believed to have a significant impact in the environment despite the relatively low environmental load ratio of 2.44.

Contents

1. Introduction

There has been considerable discussion over the past 20 years about the concept of sustainable development and its assessment. Since the onset of this debate, a large number of tools have been designed in order to capture the progress towards sustainability in a quantitative manner. A family of such techniques that has gained some acceptance amongst academics is based on thermodynamic concepts and accounts for the consumption and transformation of energy flows within a system. Methodologies that have embraced this viewpoint can be traced before the 1970s but it was the two oil crises and the accompanying concern for the need to conserve energy in industrialised nations [1] that gave a boost to their development and use. Thermodynamic accounting frameworks are generally able to capture the resource use (in the broadest sense) within a society. Whether such methodologies actually represent thermodynamic limits in a physical sense or are just a weak

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analogy or metaphor is still open to debate [2] the fact remains that they can significantly contribute to the current discussions about sustainable development. Central to all these methodologies, albeit not explicitly stated, is a common concern over resource depletion and environmental degradation [1]. The different aspects of sustainable development that can be elucidated by such tools have been discussed elsewhere in greater depth [3].

Despite the large number of sustainability assessment methodologies based on thermodynamic concepts found in the literature, in very few cases have these techniques been applied jointly on the same system. This two-part study bridges that gap by reporting on the application of four such methodologies for assessing the sustainability of the UK for the year 2004. Given that each technique illuminates certain aspects of a complex system's metabolism, integration of their findings is expected to assess more comprehensively the current production/consumption patterns and offer advice to policy makers for facilitating a shift towards sustainability. The different frameworks employed in the first part include Multi Scale Integrated Analysis of Societal Metabolism (MSIASM) and emergy synthesis (EmS) while exergy (EA) and extended exergy analysis (EEA) are employed in the second part.

Despite certain methodological differences all these techniques share several similarities. Based on the distinction between "upstream" and "downstream" impact assessment methodologies [4], all these techniques can fit into the "upstream" category given that they seem in a way to quantify the amount of resources (in the broadest sense) used to sustain human activity within a nation for a given year. Furthermore all these methodologies are in a sense biophysical sustainability accounting frameworks that are based on a "*cost of production*" theory of value rather than a "*subjective preference theory of value*" as in conventional economic analysis: refer to [5] for a distinction between the two terms and to [6] for their relevance to sustainability assessments. Furthermore, it has been claimed [7] that a theory of value based on energy can satisfy the criteria for a "*cost of production*" theory of value given that energy can be considered the "only" scarce factor of production because:

- it is ubiquitous;
- it is a property of all of the commodities produced in human and natural systems;
- its essential property cannot be substituted for.

It is worth mentioning here the similarities between the "*cost of production*" theory of value with what H.T. Odum designated as a donor-side point of valuation [8]. As a result all the biophysical tools utilized in our study fail to take into consideration human preferences and they have been criticized on these grounds in the past, e.g. [9]. However their relevance and importance for assessing the progress towards sustainability has been discussed elsewhere in the literature, e.g. [10,11]. We believe that our analysis can provide valuable information for better understanding a nation's metabolism through the utilisation of a variety of different tools based on thermodynamic concepts. MSIAM provides information on the exosomatic energy consumed in order to support human activity within various productive and "non-productive" sectors of the society. Its highly aggregated format can provide a quick snapshot of past and current trends and give hints on the sustainability of the current development path. EmS essentially quantifies the environmental support required to produce all the inputs that are consumed by the society while the total emergy consumed is an indication of its total appropriation of environmental services [4]. Finally EA and EEA make use of the concept of efficiency which has a more direct relationship with the market logic while at the same time it considers the qualitative differences between the different energy forms [4]. To better appreciate the insights relevant to sustainable development that can be provided by applying these different methodologies the reader is referenced to the introductory and methodology sections of our study and the referenced literature.

We should note that we do not view our sustainability assessment as comprehensive in the sense that it excludes human preferences (tools that employ a "subjective preference" theory of value) and does not adequately captures the consequences of a system's emissions (only "upstream" methods used). For a comprehensive sustainability assessment the inclusion of tools that are not based on thermodynamics is essential but we consider that this falls outside the scope of our study which is to highlight how tools based on thermodynamics can provide information relevant to the sustainability of a system.

The system under consideration is the United Kingdom of Great Britain and Northern Ireland (UK thereafter) for the year 2004. The 14 overseas territories as well as the territories of Jersey, Guernsey and of the Isle of Man have been excluded from our analysis.

The UK is an island nation situated in the North West of Europe having land borders only with the Republic of Ireland while it is surrounded by the Atlantic Ocean, the North Sea, the Irish Sea and the English Channel. With a population of just over 60 million the UK is both one of the most populous and one of the most densely populated European countries. It is also one of the major economies in the world, currently having the second highest gross domestic product (GDP) in Europe and the fifth highest in the world [12,13]. From a traditionally industrial nation the UK has been transformed from the 1950s onwards to a nation where the service sector spearheads the economy.

Interestingly enough the UK has significant fossil fuel reserves with their exploitation becoming economically feasible only during the 1980s as a result of the rising prices of fossil fuels initiated by the two oil crises. It is ranked amongst the 10 largest oil producing nations worldwide and together with Norway and Russia is the only European nation endowed with significant such resources. Furthermore the UK is one of the five largest producers of natural gas worldwide. Most of the oil and natural gas reserves are located offshore in the North Sea region and in order to tap these offshore fossil fuel resources the UK has claimed an extended continental shelf in the areas north and west of Scotland. The continental shelf is an important source of renewable emergy contributing significantly to a nation's wealth by providing important services such as climate mitigation, fisheries, solubilisation of nutrients from coastline, etc. However in cases such as the UK where extensive continental shelves are claimed for exploration, inclusion of the whole area of the continental shelf would overestimate the contribution of the renewable emergy sources sending misleading messages on the sustainability of the UK. In our EmS calculations we considered the continental shelf as the area of the continental margin which is between the shoreline the point where the depth of the superjacent water is approximately 200 m.

2. Methodology

2.1. MSIASM

The Multi Scale Integrated Analysis of Societal Metabolism (MSIASM) was introduced in [14–16]. The theoretical foundations of MSIASM are based on concepts popularised by Alfred Lotka and Nicholas Georgescu-Roegen [17]. In more detail MSIASM can be viewed as an operationalisation of Georgescu-Roegen bioeconomic approach that combines data on flows (exosomatic energy, GDP, food production, etc.) and funds (human time, land use, etc.) associated with the system under study (the UK in our case) [17]. Given that in this series of papers our analysis is focused on different energy accounting frameworks and the insights that they

can provide for facilitating a shift towards sustainability, exosomatic energy consumption was chosen as a flow and the allocation of human time between the different production sectors as a fund.

In particular the UK system was divided into different sectors and at different levels of hierarchy. Level n was designated as the whole society (SA), Level $n-1$ was divided into paid work sectors (PW) and household sectors (HH) while Level $n-2$ included the paid sectors of agriculture (AG), other productive sectors (PS) and the service and government sector (SG). The AG sector includes fisheries and forestry, the PS sector includes extraction and industrial activities (incl. energy industry) while the SG sector includes service and government activities. Exosomatic energy relating to transportation activities within each of these sectors was further included. A summary of the main concepts ensues but the interested reader is referred to other more comprehensive publications which present these concepts in greater detail [17–19].

Central in the MSIASM methodology is the calculation of different intensive and extensive variables. Extensive variables include:

THA Total human time for the whole society in a given year (fund element).
HAi Total human time available in sector i for a given year (fund element).
TET Total exosomatic energy consumption in the whole society for a given year (flow element).
ETi Total exosomatic energy consumption in a sector i for a given year (flow element).

The intensive variables are flow-fund, fund and flow ratios across different levels of hierarchy. Flow-fund ratios provide information on the amount of exosomatic energy invested per hour of human activity in a given sector. For example the flow-fund ratio for the paid sector ($EMR_{PW} = ET_{PW}/HA_{PW}$) denotes how much exosomatic energy has been invested for each labour hour in the paid sector as a whole. Similar flow-fund ratios can be calculated for the AG, PS and SG sectors as well as the HH sector and the society (SA) as a whole. Fund ratios indicate how much human time is used in a lower level of hierarchy compared with human activity at a higher level of hierarchy, $(n-1)/n$ and $(n-2)/(n-1)$ ratios. An example of such a ratio $(n-2/n-1)$ is that for AG sector (HA_{AG}/HA_{PW}) that denotes the amount of human labour in the agricultural sector when compared to the paid sector as a whole. Similarly flow ratios, both $(n-1)/n$ and $(n-2)/(n-1)$, show the amount of exosomatic energy used within a lower level of hierarchy when compared with exosomatic energy consumption at a higher level of hierarchy.

An MSIASM of the UK society was conducted for the years 1981 and 2004. For each year official statistics related to the exosomatic energy consumption and human labour in each sector were collected from the national statistics. Specifically, for the year 1981 exosomatic energy consumption was collected from [20], population and total work hours for the whole society from [21] and the number of employees working in the different economic sectors from data collected during the 1981 census of the UK population. For 2004 total exosomatic energy data was collected from [22], population data from [23] and work hours by economic sector through personal communication with the Office for National Statistics.

2.2. Emergy synthesis

Emergy synthesis is an energy accounting framework developed by the American ecologist H.T. Odum in the 1970s. The term emergy itself was first used by D.M. Scienceman in the 1980s to denote"*... the available energy of one kind that has been previously used up, directly and indirectly, to make a service or a product and its unit is the emjoule (ej)*" [24,25]. In fact this new term was suggested in order to replace the term embodied energy initially used by Odum after it became a mainstream through other branches of energy systems research such as energy analysis [26]. Since its inception emergy synthesis has been used to investigate and explain the interactions between ecological and human systems. Several case studies can be found in the literature with their foci being as diverse as industrial processes, agricultural systems, cities, regions and whole countries, e.g. [27–37].

Emergy synthesis is based on the two basic assumptions that in every observable phenomenon there is an energy transformation and that all these transformations can be accounted for as energy of one kind: solar energy. Deep in the core of emergy synthesis lie the understanding that different sources of energy do not have the same ability to do work and that "quality corrections" are necessary [38].

As already mentioned solar energy was chosen as the common denominator and thus the term solar emergy was born with the solar emjoule (seJ) being the common unit of measurement. One of the key concepts of emergy synthesis is solar tranformity that is defined as the solar emergy required to make 1 J of a service or a product (measured in sej J^{-1}) [8]. Generally speaking, the higher the solar/specific transformity of an input the higher the amount of solar energy that was required for the production of that product/service.

Emergy synthesis methodology has been described as a three-stage procedure that starts with the design of emergy diagrams using certain conventions and symbols summarised in [8]. Emergy diagrams are essentially a visualisation of the different emergy flows within the system under study. The different emergy flows can be summarised in the following categories (refer to Fig. 4 for an aggregated emergy diagram of the UK society for the year 2004):

- *Renewable resources R*: includes the free ecological services such as sunlight, rain, wind, waves, rivers, tides, etc. as well as renewable energy sources (hydroelectricity, Aeolian power, etc.), agricultural production, livestock and timber harvest (items 1–16 in Table 2).
- *Non-renewable production N*: includes fossil fuels, metals, minerals and soils. Non-renewable production is divided into dispersed rural resources (such as soil) (N_0) and concentrated resources (N_1).
- *Imports*: includes fuels (F), goods/minerals (G) and services (P_2I).
- *Exports*: includes fuels (N_2), goods/minerals (B) and services (P_1E).

The second step in the emergy synthesis methodology is the calculation of these diverse emergy flows and populating with these values the corresponding emergy table. The main body of the rules behind these calculations are laid in [8] but several other specific calculation procedures can be found elsewhere in the significant literature, e.g. [39].

The final stage involves the calculation of different emergy indices. These emergy indices summarise the emergy flows within the system and give insights into its production/consumption patterns as well as its sustainability. Some of the most commonly used emergy indicators include the following:

- *Emergy used per person*: aggregates the different emergy flows (R, N, F, G, P_2I) used within the system and divides it by its population. Generally speaking the higher the emergy used person the higher the standard of living in the country under study. Of course this conclusion stems from the emergy synthesis

Table 1
MSIASM variables and percentage changes for 1981 and 2004

	1981	2004	Percentage change
THA (Gh)	493.6	524.1	6.2
TET (PJ)	8312.0	9784.6	17.7
EMR_{SA} (MJ/h)	16.8	18.7	10.9
HA_{PW} (Gh)	42.7	47.6	11.3
HA_{HH} (Gh)	450.9	476.6	5.7
HA_{AG} (Gh)	1.0	0.9	−5.9
HA_{PS} (Gh)	16.2	10.7	−33.9
HA_{SG} (Gh)	25.6	36.0	40.6
TE_{PW} (PJ)	5736.4	6213.4	8.3
TE_{HH} (PJ)	2575.6	3571.1	38.7
TE_{AG} (PJ)	63.8	45.2	−29.2
TE_{PS} (PJ)	4712.6	5093.1	8.1
TE_{SG} (PJ)	960.0	1075.1	12.0
EMR_{PW} (MJ/h)	134.2	130.6	−2.7
EMR_{HH} (MJ/h)	5.7	7.5	31.2
EMR_{AG} (MJ/h)	66.4	49.9	−24.8
EMR_{PS} (MJ/h)	291.5	476.7	63.5
EMR_{SG} (MJ/h)	37.5	29.9	−20.3
Flow share PW $(n-1)/n$	69.0%	63.5%	−5.5%
Flow share HH $(n-1)/n$	31.0%	36.5%	5.5%
Flow share AG $(n-2)/(n-1)$	1.1%	0.7%	−0.4%
Flow share PS $(n-2)/(n-1)$	82.2%	82.0%	−0.2%
Flow share SG $(n-2)/(n-1)$	16.7%	17.3%	0.6%
Fund share PW $(n-1)/n$	8.7%	9.1%	0.4%
Fund share HH $(n-1)/n$	91.3%	90.9%	−0.4%
Fund share AG $(n-2)/(n-1)$	2.3%	1.9%	−0.3%
Fund share PS $(n-2)/(n-1)$	37.8%	22.5%	−15.4%
Fund share SG $(n-2)/(n-1)$	59.9%	75.6%	15.7%

assumption that the "real wealth" of a nation depends on the natural resources consumed within that nation rather than its economic production.

- *Emergy investment ratio* (*EIR*): the ratio of purchased emergy flows to a society divided by the free emergy inputs (indigenous). The lower this ratio the more an economy relies on local ("free") indigenous inputs. It is believed that the higher this ratio the higher the economic development of a system [32].
- *Environmental load ratio* (*ELR*): denotes the ratio of the non-renewable emergy flows consumed within a system divided by the renewable emergy flows for that system. High environmental loading ratios imply high environmental stresses.
- *Empower density*: is the ratio of the emergy used within the system divided by the total area of the system. High empower densities are usually a characteristic of industrialised nations.

3. Results and discussion

3.1. MSIASM

Exosomatic energy consumption statistics are collected from official energy statistics. However, in order to account for the contribution of transport to the exosomatic energy consumption of each economic sector transport energy statistics from [22] had to be re-allocated to the different end-sectors. Such data for the year 2004 were collected from [40]. In particular of the 2435.3 PJ of the exosomatic energy consumed for transport activities 1536.9 PJ were consumed by the HH sector, 6.8 PJ by AG, 622.7 by PS and 268.9 PJ by SG. It should be noted here that AG transport data are not readily available in [40] but are aggregated with the service transport data. In order to differentiate transport relevant to AG and SG it was assumed that the exosomatic energy consumption in each of the two sectors was proportional to the labour hours in the AG and SG sectors. A similar analysis has been pursued in Part 2 of our study and although it seems reasonable it is quite uncertain. Moreover, such transport energy consumption data have been recorded only for the period 1990–2004 and they do not show a specific trend. It was assumed that for the year 1981 the re-allocation to final end-sectors was equal to the average numbers for the period 1990–1993. As a result 24% of the energy used for transport was attributed to the industrial sector, 63% to the domestic sector and 13% to the service sector (incl. agriculture).

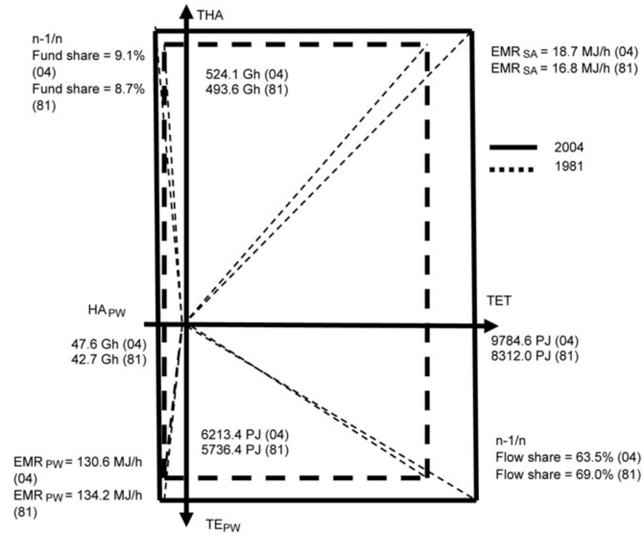


Fig. 1. Flow-fund representation of the UK MSIASM (1981 and 2004).

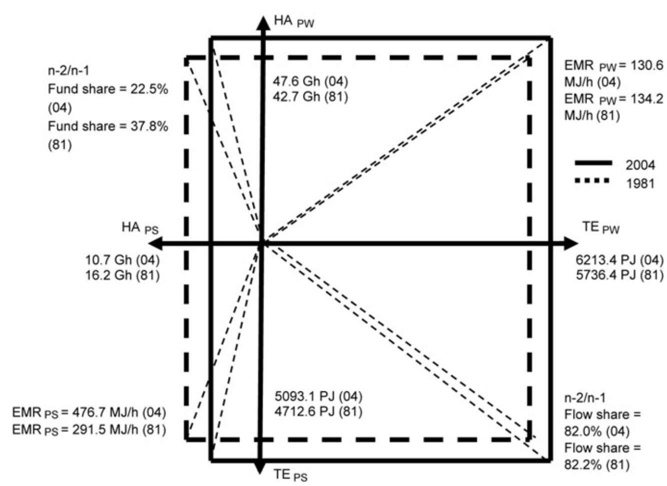


Fig. 2. Flow-fund representation of the UK PS sector MSIASM (1981 and 2004).

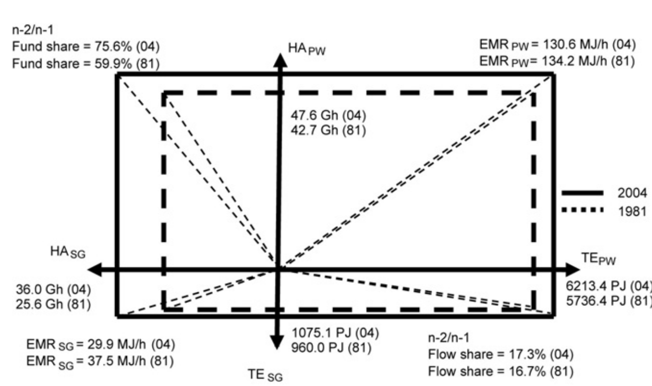


Fig. 3. Flow-fund representation of the UK SG sector MSIASM (1981 and 2004).

Following the same procedure described earlier it was calculated that of the 1437.3 PJ of energy consumed by transport activities during 1981, 908.9 PJ were consumed in the HH sector, 6.7 PJ in the AG sector, 343.6 PJ in the PS sector and 178.1 in the SG sector. All the relevant results and the corresponding differences in the period 1981–2004 are included in Table 1.

During that period there was a slight population increase of about 6.2%. During the same period, however, there was a disproportionate increase of the total exosomatic energy consumed. Specifically total exosomatic energy consumption rose from 8312.0 PJ in 1981 to 9784.6 PJ in 2004 which corresponded to a 17.7% increase. For 2004 the EMR_{SA} of the UK was in the order of 18.7 MJ/h (up from 16.8 MJ/h in 1981). The calculated EMR_{SA} is significantly higher than the world EMR_{SA} in 1999 which was 7.8 MJ/h and was comparable to that of the OECD countries (22.3 MJ/h) [17].

Moving our analysis to the $(n-1)$ level we can gain some information on the trends that govern paid work sectors and the households. As expected as a result of the population increase there was an increase in the human time in both the paid work sector and the households. This increase was much higher, and well above the population increase, in the working sectors

Table 2
Emergy evaluation of the UK

Note	Item	Raw data	Units	Transformity (seJ/unit)	Solar emergy ($\times 10^{21}$ seJ)
Renewable resources					
1	Sun, incident	2.60E + 21	J	1.00E + 00	2.6
1	Sun, absorbed	2.34E + 21	J	1.00E + 00	2.3
2	Wind kinetic energy	6.78E + 19	J	2.47E + 03	167.7
3	Earth cycle	7.58E + 17	J	5.76E + 04	43.7
4	Rain, chemical potential energy	2.04E + 18	J	3.12E + 04	63.7
5	Evapotranspiration, chemical potential energy	6.55E + 17	J	4.80E + 04	31.4
6	Rain, geopotential on land	2.39E + 17	J	1.76E + 04	4.2
7	Rivers, chemical potential energy	7.43E + 17	J	8.13E + 04	60.4
8	Rivers, geopotential energy	1.69E + 17	J	4.66E + 04	7.9
9	Wave energy	2.78E + 19	J	5.13E + 04	1428.9
10	Tidal energy	2.02E + 19	J	2.82E + 04	571.2
Renewable production					
11	Agricultural and livestock production	4.84E + 17	J	1.19E + 06	574.8
12	Fish production	4.22E + 15	J	3.35E + 06	14.1
13	Hydro electricity	2.73E + 16	J	1.04E + 05	2.9
14	Wind electricity	6.95E + 15	J	1.04E + 05	0.7
15	Ground water	6.97E + 16	J	2.72E + 05	18.9
16	Timber harvest	1.36E + 17	J	1.17E + 05	15.9
Production and use of non-renewable					
17	Coal production	6.55E + 17	J	6.71E + 04	43.9
18	Coal used	1.62E + 18	J	6.71E + 04	108.7
19	Natural gas production	4.02E + 18	J	7.29E + 04	293.3
20	Natural gas used	4.06E + 18	J	7.29E + 04	296.2
21	Crude oil production	4.38E + 18	J	9.09E + 04	398.1
22	Crude oil used	4.28E + 18	J	9.09E + 04	389.0
23	Electricity production (other than wind, hydro)	1.39E + 18	J	2.91E + 05	404.5
24	Electricity used	3.99E + 17	J	2.91E + 05	116.3
25	Clay	1.54E + 13	g	3.35E + 09	51.6
26	Sand and gravel	9.73E + 13	g	2.24E + 09	218.0
27	Sandstone	1.88E + 13	g	1.68E + 09	31.7
28	Limestone and dolomite	1.02E + 14	g	1.68E + 09	171.1
29	Silica sand	5.01E + 12	g	1.68E + 09	8.4
30	Salt rock	5.80E + 12	g	1.68E + 09	9.7
31	Igneous rock	5.30E + 13	g	1.68E + 09	88.9
32	Gypsum	1.69E + 12	g	1.68E + 09	2.8
33	Peat	1.35E + 16	J	1.70E + 04	0.2
34	Soil erosion from agricultural areas	2.24E + 16	J	1.24E + 05	2.8
Imports					
35	Coal	9.89E + 17	J	6.71E + 04	66.3
36	Crude oil	4.79E + 17	J	9.09E + 04	43.5
37	Petroleum products and manufactured fuel	2.86E + 18	J	1.11E + 05	316.1
38	Natural gas	8.75E + 17	J	7.29E + 04	63.8
39	Electricity	3.52E + 16	J	2.91E + 05	10.3
40	Imports goods	Various	J, g	Various	1503.4
41	Imports services/services embodied to goods	6.07E + 11	USD	1.88E + 12	1140.0
Exports					
42	Coal	1.88E + 16	J	6.71E + 04	1.3
43	Crude oil	2.95E + 18	J	9.09E + 04	268.1
44	Petroleum products and manufactured fuel	1.47E + 18	J	1.11E + 05	163.2
45	Natural gas	4.11E + 17	J	7.29E + 04	30.0
46	Electricity	8.25E + 15	J	2.91E + 05	2.4
47	Exports goods	Various	J, g	Various	592.8
48	Exports services/services embodied to goods	5.43E + 11	USD	2.63E + 12	1447.2

Transformity references 1. by definition, 2. [43], 3. [43], 4. [8], 5. [8], 6. [8], 7. [8], 8. [8], 9. [8], 10. [8], 11. this study (Table 3), 12. [39], 13. [27], 14. [27], 15. [39], 16. [39], 17. [8], 18. [8], 19. [44], 20. [44], 21. [44], 22. [44], 23. [8], 24. [8], 25. [8], 26. [39], 27. [8], 28. [8], 29. [8], 30. [8], 31. [8], 32. [8], 33. [8], 34. [8], 35. [8], 36. [44], 37. [8], 38. [44], 39. [8], 40. various, 41. [45], 42. [8], 43. [44], 44. [8], 45. [44], 46. [8], 47. various and 48. this study.

Table 3
Emergy evaluation of the UK agriculture and livestock production

Note	Item	Raw data	Units	Transformity (seJ/unit)	Solar emergy ($\times 10^{21}$ seJ)
Inputs					
1	Solar energy received	6.33E + 20	J	1.00E + 00	0.6
1	Solar energy absorbed	5.70E + 20	J	1.00E + 00	0.6
2	Kinetic energy wind (land)	1.29E + 20	J	2.47E + 03	318.3
3	Earth cycle energy	1.84E + 17	J	5.76E + 04	10.6
4	Rain chemical potential	7.95E + 17	J	3.12E + 04	24.8
5	Chemical potential energy of evapotranspiration	5.80E + 17	J	4.80E + 04	27.8
6	Coal	2.09E + 14	J	6.71E + 04	0.0
7	Natural gas	8.46E + 15	J	7.29E + 04	0.6
8	Petroleum products and manufactured fuel	1.16E + 16	J	1.11E + 05	1.3
9	Electricity	1.51E + 16	J	2.91E + 05	4.4
10	Limestone/dolomite/chalk	1.89E + 12	g	1.68E + 09	3.2
11	Silica sand	8.38E + 11	g	1.68E + 09	1.4
12	Feed and seed	1.73E + 17	J	various	54.8
13	Nitrogen fertilizers, N	1.26E + 12	g	2.41E + 10	30.4
14	Phosphate fertilizers, P	6.66E + 10	g	2.20E + 10	1.5
15	Potassium fertilizers, K	1.68E + 11	g	1.74E + 10	2.9
16	Pesticides	3.10E + 10	g	1.48E + 10	0.5
17	Domestic goods and services	2.07E + 10	USD	2.66E + 12	55.2
18	Imported services/services embodied in imported goods	1.13E + 10	USD	1.88E + 12	21.1
19	Compensation of employees	5.76E + 09	USD	2.66E + 12	15.3
Outputs					
20	Crops	4.02E + 17	J		
21	Livestock	8.21E + 16	J		

Transformity references 1. by definition, 2. [43], 3. [43], 4. [8], 5. [8], 6. [8], 7. [44], 8. [8], 9. [8], 10. [8], 11. [8], 12. various, 13. [46], 14. [46], 15. [46], 16. [46], 17. this study, 18. [45] and 19. this study.

(11.3%) than the households (5.7%). The moderate increase of the $(n-1)/n$ fund share for PW between that period from 8.7% to 9.1% indicated a marginal increase of the total human activity diverted to the working sectors. On the other hand, the increase in the exosomatic energy consumed in the households was tremendous (38.7%) when compared to that in the paid work sectors (8.3%). This disproportionate increase can be attributed to a great extent in the increasing demand for transport within the household sector that is usually met through increased private car ownership.

Moving to the lowest level, $(n-2)$, several patterns governing the different paid work sectors can be discerned. One of the most striking results is the large decrease of human activity in the productive sectors (PS) of 33.9%, which happened with a simultaneous increase in the consumption of exosomatic energy by 8.1%. This implies increased industrial activity with fewer labour hours involved and is also evident in the sharp rise of the EMR_{PS} by 63.5%. Patterns towards the decrease of both the overall human activity and the exosomatic energy consumed were evident in the AG sector. The decrease was in the order of 5.9% in the former and 29.2% in the latter case. On the other hand the situation in the SG is quite distinct as it comes at complete odds with the situation in the other working sectors. The exosomatic energy consumption rose by 12% while the allocation of the human time by a massive 40.6%. As a result of these changes EMR_{AG} and EMR_{SG} decreased by 24.8% and 20.3%, respectively. The observed shift in the UK economy from the predominance of the industrial production to that of services is also implied and from the decrease of the PS fund share by 15.4% coupled with the simultaneous increase of the SG fund share by 15.7%.

All the aforementioned research results are graphically presented in Figs. 1–3.

Table 4
Summary emergy flows of the UK economy

Note	Item	Value	Unit
R	Renewable emergy absorbed	1640.3	10^{21} seJ
	Wind kinetic energy	167.7	10^{21} seJ
	Earth cycle	43.7	10^{21} seJ
	Wave energy	1428.9	10^{21} seJ
N	Non-renewable resources within the UK	1320.7	10^{21} seJ
N_0	Dispersed rural sources	2.8	10^{21} seJ
N_1	Mineral production (fuels, minerals, etc.)	1317.9	10^{21} seJ
N_2	Fuels exported without use	462.5	10^{21} seJ
F	Imported fuels (incl. electricity)	500.1	10^{21} seJ
G	Imported goods and minerals	1503.4	10^{21} seJ
I	Imported services (USD)	6.07E + 11	USD
P_2I	Imported services (emergy value)	1140.0	10^{21} seJ
B	Exported goods (including electricity)	595.2	10^{21} seJ
E	Exported services (USD)	5.43E + 11	USD
P_1E	Exported services (emergy value)	1447.2	10^{21} seJ
X	Gross national product	2.12E + 12	USD
P_1	UK emergy-to-money ratio	2.66E + 12	seJ/USD
P_2	Trade partner's emergy-to-money ratio	1.88E + 24	seJ/USD

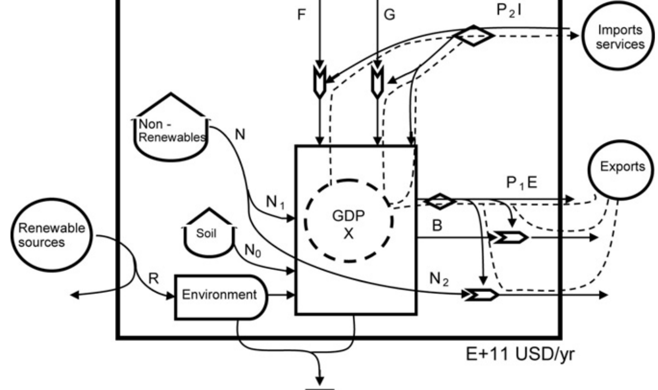


Fig. 4. Aggregated emergy flows for the UK economy.

Table 5
Emergy indices for the UK economy

Note	Item	Value
In state non-renewable	$N_0 + N_1$	1320.7×10^{21} seJ
Imported emergy	$F + G + P_2I$	3143.4×10^{21} seJ
Total emergy used	$U = R + N_0 + N_1 + F + G + P_2I - N_2$	5641.9×10^{21} seJ
Total exported emergy	$N_2 + B + P_1E$	2504.9×10^{21} seJ
Emergy used from home sources	$(N_0 + N_1 - N_2 + R)/U$	0.443
Imports–exports	$(F + G + P_2I) - (N_2 + B + P_1E)$	638.5×10^{21} seJ
Ratio of exports to imports	$(F + G + P_2I)/(N_2 + B + P_1E)$	1.255
Fraction use, locally renewable	R/U	0.291
Fraction of use, purchased import	$(F + G + P_2I)/U$	0.557
Fraction used, imported service	P_2I/U	0.202
Fraction used, exported services	P_1E/U	0.257
Emergy investment ratio (purchased/free)	$(F + G + P_2I)/(R + N - N_2)$	1.258
Environmental loading ratio	$(N - N_2 + G + P_2I)/R$	2.440
Solar emergy unit per unit area (empower density)	U/area	7.44E + 12 seJ/m^2
Solar emergy used per person	U/population	9.43E + 16 seJ/person
Emergy yield ratio	$U/(F + G + P_2I)$	1.795

3.2. Emergy synthesis

Of the renewable emergy resources, waves and tides were the greatest contributors of renewable emergy in the UK which comes as no surprise considering the fact that the UK is an island nation. In more detail 29.1% (1640.3×10^{21} seJ) of the emergy used within the UK came from local renewable sources. It should be noted here that in order to avoid double counting these renewable resource inputs only the highest contributors relevant to the three planetary processes (sun, earth heat and tide) have been considered for the aggregate flow R (refer to Table 2) [8]. In our calculations these items were emergy from wind, earth cycle and waves, respectively (refer to Table 4). Of the renewable production by far the greatest contributor was agriculture and livestock production with 574.8×10^{21} seJ. It should be noted here that the values of transformities and specific emergies used in this study are relative to the 15.83 baseline.

Table 3 contains a detailed analysis of the UK agricultural and livestock production for the year 2004. It is evident that renewable emergy inputs such as the items 1–5 in Table 3 are the most important inputs to the UK agricultural system amounting for almost 66.6% of the total emergy inputs. Feed/seed and human services were also important. Our analysis established an aggregate transformity of 1.19E + 06 seJ/J for agricultural and livestock products produced in the UK in 2004. It is worth mentioning here that the energy content of the agricultural production (items 20 and 21 of Table 3) was calculated based on the analysis of over 200 agricultural commodities including cereals, fruits, livestock and fish product amongst others which were retrieved from the statistical database of the United Nations Food and Agriculture Organisation [41]. Production statistics were calculated for 2004 while feed and seed statistics for 2003. Energy content of the different commodities was retrieved from the US Department of Agriculture [42]. Some detailed results for the energy content of major agricultural product categories are included in Section 3.2 of Part 2 of our study.

Crude oil and natural gas were the most important, by emergy value, non-renewable resources produced and consumed within the UK with coal, minerals and soils also contributing but to a lesser extent. Fuels also constituted major emergy import and export flows to/from the UK. Total in state non-renewable emergy flows amounted to 1320.7×10^{21} seJ (refer to Tables 4 and 5).

In our analysis imports and exports were aggregated into three major categories: fuels and minerals, goods and services. Emergy flows from imported/exported goods are obtained through the aggregation of the emergy flows of over 30 different product categories as diverse as metals, chemicals, wood products, textiles, etc. Imports of goods and minerals (G) amounted to 1503.4×10^{21} seJ. Export of fuels without use (N_2) was in the order 462.5×10^{21} which was comparable to the 595.2×10^{21} seJ of exported goods (B) (including small amounts of electricity). This shows again the importance of the North Sea oil fields to the UK economy. UK also imported 1140.0×10^{21} seJ in direct services and services embodied to the goods (P_2I) while it exported 1447.2×10^{21} seJ of services (P_1E). These flows are summarised in Fig. 4 and Table 4.

In total the UK was a net emergy importer of 638.5×10^{21} seJ while its imported emergy accounted for 55.7% of the emergy used within the UK with the main contributor to that being imported goods and minerals (G). Emergy from home sources contributed just 44.3% of the total emergy used within the UK. This figure is quite small considering UK's significant natural resource reserves.

The UK showed an emergy investment ratio (EIR) of about 1.3, which is quite low, implies that the UK gets a high proportion of its emergy free from the environment depending significantly on local "free" resources something that has already been discussed. What is more interesting though is that the UK has an environmental loading ratio (ELR) of about 2.4 which is quite low for a developed nation (refer to [32]). This low value can probably be explained by the significant renewable emergy input in the extensive continental shelf area as well as the large amount of fossil fuel exported. Despite the fact that low environmental ELRs imply low stress to the environment we believe that for the UK this is not the case as explained in the previous sentence. Given the UK's emergy-to-money ratio is higher than the rest of the world the UK exports more emergy than it actually gets in a dollar-to-dollar trade exchange regime which is also quite unusual for a developed nation. The emergy yield ratio (EYR) of approximately 1.8 implies that almost two times more emergy is used within the UK system than imported in it.

4. Conclusions

The MSIASM analysis of the UK economy has shown an important trend towards the shift of economic activity from agriculture (AG) and productive sectors (PS) to the service and government (SG) sector. Longitudal data mainly in the allocation of human time within these three sectors and to a lesser extent in the consumption of exosomatic energy illustrate this situation. Furthermore there is a disproportionate increase of the exosomatic energy consumption by the household sector (HH) when compared with the increase of human time in households mainly

due to the increased demand for transport by the HH sector over the 1981–2004 period.

Of the exosomatic emergy consumed the most significant contributors were oil and natural gas (or electricity produced by it) most of which entered the UK as a "free" emergy input from the North Sea. The UK economy also benefited to a great extent from the significant inputs of renewable emergy (wind, earth cycle and waves), which accounted for almost a third of all emergy used within the UK. In general our analysis found a relatively low emergy investment ratio (EIR), which implied that the UK obtained a high proportion of its emergy free from the environment depending significantly on local "free" resources. Finally, the UK was a net emergy exporter mainly as a result of disproportionate imports of goods (G) when compared to exports of goods (B). This disproportionate import of goods can partly be linked to the continuing trend of shifting from industrial production to services during the period 1981–2004.

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References

[1] Hammond GP. Industrial energy analysis, thermodynamics and sustainability. Appl Energy 2007;84:675–700.
[2] Hammond GP. Engineering sustainability: thermodynamics, energy systems and the environment. Int J Energy Res 2004;28:613–39.
[3] Gasparatos A, El-Haram M, Horner M. A critical review of reductionist approaches for assessing the progress towards sustainability. Environ Impact Assess Rev 2007;28:286–321.
[4] Ulgiati S, Raugei M, Bargigli S. Overcoming the inadequacy of single criterion approaches to life cycle assessment. Ecol Model 2006;190:432–42.
[5] Patterson M. Commensuration and theories of values in ecological economics. Ecol Econ 1998;25:105–25.
[6] Gasparatos A, El-Haram M, Horner M. The argument against a reductionist approach for assessing sustainability. In: Horner M, Hardcastle C, Price A, Bebbington J, editors. Proceedings of the International Conference on Whole Life Urban Sustainability and its Assessment, 27–29 June. 2007. p. 52–65.
[7] Farber CS, Costanza R, Wilson MA. Economic and ecological concepts for valuing ecosystem services. Ecol Econ 2002;41:375–92.
[8] Odum HT. Environmental accounting: emergy and environmental decision making. New York: Wiley & Sons Inc.; 1996.
[9] Cleveland CJ, Kaufmann RK, Stern DI. Aggregation and the role of energy in the economy. Ecol Econ 2000;32:301–17.
[10] Ecological Economics: Ecological Economics Forum. Why sustainability analyses must include biophysical assessments. Ecol Econ 1999;29:13–60.
[11] Munasighe M, Shearer W. Defining and measuring sustainability: the biogeophysical foundations. Washington DC: The World Bank; 1995.
[12] World Bank. Total GDP 2006. Washington DC: World Bank; 2005, Available at http://siteresources .worldbank.org/DATASTATISTICS/Resources/GDP.pdf (last accessed April 2007).
[13] IMF. World economic output database. Washington DC: International Monetary Fund; 2007, Available at http://www.imf.org/external/pubs/ft/weo/2007/01/data/index.aspx (last accessed April 2007).
[14] Giampietro M, Mayumi K. A dynamic model of socioeconomic systems based on hierarchy theory and its application to sustainability. Struct Change Econ Dyn 1997;8:453–69.
[15] Giampietro M, Mayumi K. Multiple-scale integrated assessment of societal metabolism: introducing the approach. Popul Environ 2000;22:109–53.
[16] Giampietro M, Mayumi K. Multiple-scale integrated assessment of societal metabolism: integrating biophysical and economic representations across scales. Popul Environ 2000;22:155–210.
[17] Ramos-Martin J, Giampietro M, Mayumi K. On China's exosomatic energy metabolism: An application of multi-scale integrated analysis of societal metabolism (MSIASM). Ecol Econ 2007;63:174–91.
[18] Giampietro M, Ramos-Martin J. Multi-scale integrated analysis of sustainability: a methodological tool to improve the quality of narratives. Int J Global Environ Issues 2005;5:119–41.
[19] Ramos-Martin J, Giampietro M. Multi-scale integrated analysis of societal metabolism: learning from trajectories of development and building robust scenarios. Int J Global Environ Issues 2005;5:225–63.
[20] DE, 1982. Digest of United Kingdom Energy Statistics. London: Department of Energy; 1981.
[21] ONS. Total actual weekly hours worked (millions). Time series data. London: Office for National Statistics; 2007, Available at http://www.statistics.gov.uk/statbase/tsdtimezone.asp (last accessed May 2007).
[22] DTI. Digest of United Kingdom Energy Statistics 2006 URN No: 06/87. London: Department of Trade and Industry; 2006 , Available at http://www.dtistats.net/energystats/dukes06.pdf.
[23] ONS. Resident population: mid year estimates. Time series data. London: Office for National Statistics; 2007 , Available at http://www.statistics.gov.uk/statbase/tsdtimezone.asp (last accessed May 2007).
[24] Odum HT. Self organisation, transformity, and information. Science 1988;242:1132–9.
[25] Scienceman DM. Energy and emergy. In: Pillet G, Murota T, editors. Environmental Economics: The Analysis of a Major Interface. Geneva: Rolland Leimgruber; 1987. p. 257–76.
[26] Hammond GP. Energy and sustainability in a complex world: reflections on the ideas of Howard T. Odum. Int J Energy Res 2007;31:1105–30.
[27] Brown MT, Ulgiati S. Emergy evaluations and environmental loading of electricity production systems. J Clean Prod 2002;10:321–34.
[28] Cohen MJ, Brown MT, Shepherd KD. Estimating the environmental costs of soil erosion at multiple scales in Kenya using emergy synthesis. Agric Ecosyst Environ 2006;114:249–69.
[29] Higgins JB. Emergy analysis of the oak openings region. Ecol Energy 2003;21:75–109.
[30] Huang SL, Odum HT. Ecology and economy: emergy synthesis and public policy in Taiwan. J Environ Manage 1991;32:313–33.
[31] Jiang MM, Chen B, Zhou JB, Tao FR, Li Z, Yang ZF, Chen GQ. Emergy account for biomass resource exploitation by agriculture in China. Energy Policy 2007;35:4704–19.
[32] Jiang MM, Zhou JB, Chen B, Chen GQ. Emergy-based ecological accounts for the Chinese economy in 2004. Commun Nonlinear Sci Numer Simul 2008;13:2337–56.
[33] Lefroy E, Rydberg T. Emergy evaluation of three cropping systems in southwestern Australia. Ecol Model 2003;161:193–209.
[34] Martin JF. Emergy valuation of diversions of river water to marshes in the Mississippi River Delta. Ecol Energy 2002;18:265–86.
[35] Tilley DR, Brown MT. Dynamic emergy accounting for assessing the environmental benefits of subtropical wetland stormwater management systems. Ecol Model 2006;192:327–61.
[36] Ulgiati S, Odum HT, Bastianoni S. Emergy use, environmental loading and sustainability an emergy analysis of Italy. Ecol Model 1994;73:215–68.
[37] Zhang LX, Yang ZF, Chen GQ. Emergy analysis of cropping–grazing system in Inner Mongolia Autonomous Region, China. Energy Policy 2007;35:3843–55.
[38] Brown MT, Ulgiati S. Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems. Ecol Model 2004;178:201–21.
[39] Campbell DE, Brandt-Williams SL, Meisch, MEA. Environmental accounting using emergy: evaluation of the state of West Virginia. Narragansett: United States Environmental Protection Agency; 2005. Available at http://www.epa.gov/nheerl/publications/files/wvevaluationposted.pdf.
[40] DTI. Energy consumption in the United Kingdom. URN No: 02/1049. London: Department of Trade and Industry; 2006. Available at http://www.berr.gov.uk/files/file11250.pdf.
[41] FAO. Statistical Database, FAOSTAT. Rome: Food and Agriculture Organization of the United Nations; 2007, Available at http://faostat.fao.org/ (last accessed April 2007).
[42] USDA. National Nutrient Database for Standard Reference. United States Department of Agriculture: 2007. Available at http://www.nal.usda.gov/fnic/foodcomp/search/ (last accessed April 2007).
[43] Odum, HT. Handbook of emergy evaluation. Folio #2. Emergy of global processes. Gainsville: Centre for Environmental Policy, University of Florida; 2000. Available at http://www.epa.gov/aed/html/collaboration/emergycourse/presentations/Folio2.pdf.
[44] Bastianoni S, Campbell D, Susani L, Tiezzi E. The solar transformity of oil and petroleum natural gas. Ecol Model 2005;186:212–20.
[45] Brown MT, Ulgiati S. Emergy evaluation of the biosphere and natural capital. AMBIO 1999;28:486–93.
[46] Brandt-Williams, SL. Handbook of emergy evaluation. Folio #4. Emergy of Florida agriculture. Gainesville: Centre for Environmental Policy, University of Florida; 2002. Available at http://www.epa.gov/aed/html/collaboration/emergycourse/presentations/Folio4.pdf.